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SIMULATION STUDIES OF SST TERMINAL AREA NAVIGATION

IN THE ATC SYSTEM

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PRECIS OF CONTENTS AND CONCLUSIONS

1. The current joint NASA-FAA simulator program, designed to study the problems anticipated in the introduction of the supersonic transport into the air traffic control system, is explained. The initial tests have consisted of simulated departure and arrival operations of a variable-sweep-SST configuration (NASA SCAT 16) in the New York terminal area under high-density traffic flow conditions with as many as six SST operations per hour. Several types of separation standards and handling concepts were investigated while using an air traffic control system based on present-day concepts and procedures.

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2. Results pertinent to navigation problems have shown that for departures, in order to avoid serious effects on SST performance and prevent intensification of the sonic boom, appreciable heading changes should be accomplished at subsonic speeds. A transonic acceleration track approximately 100 nautical miles long in which neither heading nor altitude restrictions are required, is desirable. Also appreciable heading changes at supersonic speeds were found to create a problem in that unless a lead-type turn is executed, the resulting overshoot at the intersection creates the need for increased separation requirements. Difficulty in vertical flight path control, particularly at supersonic speeds in the climbouts, has indicated the need for new flight instrumentation. Workload for the SST crew associated with operating in the air traffic control system appears to be increased over that for subsonic jet transports.

3. For the air traffic control system, in operations in which the SST was given priority, subsonic traffic incurred long radar vectors, excessive holding, and ground delays. Further, airport acceptance rates were substantially reduced, in some cases by 14 operations per hour. However, limited preferential treatment can be provided the SST without adverse effect on the current ATC system. Present voice communications procedures appear to be adequate for SST operations. It appears that more expeditious ATC handling for the SST would be possible by provision of segregated approach and departure routes.

4. Future studies will include other potential designs for the SST, and updating of the SST instrumentation and the air traffic control system concepts to those envisioned for the 1970-1975 time period.

INTRODUCTION

5. In order to study the problems anticipated in connection with the introduction of the supersonic transport into the air traffic control system, the NASA and FAA have initiated a cooperative research program. This program is making use of a supersonic transport simulator located at NASA Langley Research Center, Hampton, Virginia, and the air traffic control simulator located at the FAA's National Aviation Facility Experimental Center, Atlantic City, New Jersey. By means of data and voice links connecting these facilities, projected designs of the SST are being flown in real-time air traffic control environments.

6. The objectives of the program are (1) to determine the effects of the ATC system on SST design and equipment requirements, and (2) to determine the effects of the SST on ATC system requirements.

7. In this paper, results of initial studies pertinent to navigation problems for one SST design in terminal area operations while using the present-day airways system and current ATC procedures are given.

EQUIPMENT

8. SST simulator.- The flight compartment and flight instrumentation of the SST simulator (fig. 1) are similar to those of current jet transport aircraft with instrument ranges modified only to cover the higher altitude and Mach number operation of the SST. Accessory equipment needed to provide for navigation, communication, data transmission, recording, and power requirements is located in a room behind the cockpit (fig. 2). The navigation equipment includes the capability of simulating up to 6 VHF omni-range (VOR) stations with distance measuring equipment (DME), marker beacons, and instrument landing system (ILS). The communications equipment provides the switching capability required in implementing the simulated VHF radio communications between the pilots and air traffic controllers over telephone lines. A dual channel tape recorder is provided for preserving air-to-ground and ground-to-air communications. Two X-Y recorders provide for continuous ground track recording.

9. In addition to the above equipment, five Electronics Associates 231R analog computers are used to solve six-degree-of-freedom motion equations for an aircraft having the characteristics of a supersonic transport design. Signals from the pilot's control motions are converted into the proper aircraft instrument indications by means of this analog computer program. The computer program is scaled to cover a Mach number range from 0 to 4.0 and an altitude range from sea level to 100,000 feet. The characteristics of the engines, autopilot, and other aircraft systems are also programed in the analog computer.

10. Four eight-channel recorders are used to obtain time histories of aircraft motions, speeds, accelerations, and performance parameters.

11. ATC simulation.- The real-time simulated ATC environment is created by means of representative air traffic control facilities and air traffic samples. Both simulations are provided by the FAA and create the environment in which the SST simulator is operated for the tests.

12. The air traffic control facilities simulated consist of an Air Route Traffic Control Center (ARTCC), with adjoining ARTC center sectors, and an approach control and tower complex for one airport. The area controlled is 400 nautical miles by 400 nautical miles. Figure 3 shows part of an Air Traffic Control Facility similar to that

being used in the subject program. These facilities are operated by approximately 30 experienced air traffic controllers. The controllers are provided with modern TV-type bright radar displays with video maps showing airways, holding and terminal areas, and navigation aids - as well as the usual flight progress strips and interphone and radio communications equipment.

13. The air traffic sample simulation is created by 60 electronic target generators. A photograph of some of the target generators is shown in figure 4. The target generators are operated by "pilots" (operators) who manipulate their simulated aircraft along the airways system and departure and arrival paths according to a preprogramed script and instructions from the controllers over a simulated radio communications network. Each target generator is programed to have the generalized characteristics of a particular type of aircraft. A number of types of aircraft are programed in order to create the required traffic mix. The outputs of the target generators feed radar simulators which transform the target position data into radar form; i.e., pulses and antenna position. Thus, the output of the radar simulators is in the form of properly gated target video pulses and antenna position data which duplicates that of the radar being simulated. The video targets from the radar simulators are fed to the controllers' displays. Three types of radar simulators are provided; airport surveillance, long range, and precision approach. The basic capabilities of the ATC simulator are given in Table I.

14. The data collection and reduction system collects and reduces data to help evaluate a particular system under test. Information relating to conflictions, traffic density as a function of area (or sector), landing rates, changes in flight plan required by control, communications usage, etc., is provided by this portion of the simulator so that system performance can be determined in a minimum time after a simulated problem has been completed.

15. Data transmission and communications.- Data transmission between the SST simulator and the ATC simulation facilities is effected over leased private telephone lines. The SST simulator ground coordinates (X-Y), altitude (Z) information, and radar beacon transponder signals are transmitted over this system. The SST position and transponder information joins the same information from the target generators for display on the controller's radar displays.

16. Communications between the radar target generator operators and the air traffic controllers is effected by means of an internal telephone switching system. This system is an extremely versatile telephone system which allows many operators to dial the same controller simultaneously, thus simulating actual radio communications. Communications between the pilots of the SST simulator and the controllers is effected over two leased telephone lines which are connected into the internal telephone switching system. The dialing in this case is done by an operator at the SST simulator communications console in accordance with the radio frequencies selected by the pilots.

TEST PROGRAM

17. General.- The test program was designed to study arrival and departure operations of the supersonic transport to and from the Kennedy International Airport in the multi-airport New York area. A mixed traffic sample representing conditions of high-density traffic flow including SST aircraft, one of which is the SST simulator, was used. All traffic was under positive control of the New York Air Route Traffic Control Center, adjacent centers, and Kennedy Departure, Arrival, and Tower Facilities.

18. SST characteristics and operations.- For the initial tests herein reported, a variable-sweep SST design (NASA SCAT 16) was used. The program of wing sweep with Mach number was accomplished automatically. Afterburning turbo jet-type engines sized for cruising without afterburning were simulated. The basic aircraft damping was augmented about all three axes to provide satisfactory handling qualities. Piloting was done by United Air Lines and Trans World Airlines crews familiar with operations in the New York area. Manual control was used both for horizontal and vertical flight path control. The flight instrumentation included a Bendix 300 Flight Director System.

19. The climb and descent schedules and operating limits are shown in figure 5. For the ascent, after the initial accelerated climb following takeoff, a climb at 360 knots IAS is used up to 40,000 feet, a Mach altitude schedule representing a sonic boom overpressure limit of 2.0 pounds per square foot is followed up to 51,000 feet, and a climb at 570 knots IAS is used to cruise conditions of a Mach number of 3.0 at 65,000 feet. Full afterburning was employed upon reaching an altitude of about 20,000 feet and continued until approaching cruise conditions. For the descent, a slowup at cruise altitude is made from a Mach number of 3.0 to an indicated airspeed of 340 knots. Descent is then made at 340 KIAS to 50,000 feet where the aircraft is further slowed to a Mach number of 0.9. Further descent is made at a Mach number of 0.9 until 340 KIAS is again reached. The remainder of the descent is made at 340 KIAS until the holding area is approached where the aircraft is slowed to a holding speed of 250 KIAS. The descent schedule was designed to keep the sonic boom overpressure below 1.5 pounds per square foot. Deceleration in the descent was accomplished by idling the engines to a level of 7 percent of maximum unaugmented thrust and employing speed brakes. A limitation of 0.2g in longitudinal deceleration for passenger comfort was imposed on the operation. In some cases, the pilots employed in-flight thrust reversal to steepen the descent in order to arrive over a fix at the correct altitude.

ENVIRONMENT

20. ATC environment and procedures.- The Air Traffic Control simulation sample represented the New York Terminal and En Route area at peak activity conditions (148 operations in the New York Terminal area per hour including six SST operations) with arrivals and departures to and from the John F. Kennedy International Airport. Oceanic flights transited the Boston Air Route Traffic Control Center and the New York oceanic control areas. In preliminary transcontinental tests, flights were initiated or terminated about 100 nautical miles West of John F. Kennedy International Airport.

21. In the initial phases of the program, the objective was to study the Supersonic Transport in the current ATC system to provide a comparison base for further tests with possible improvements to the SST and the ATC system.

Tests were made in real time as follows:

1. High priority for SST's (clear track, no restrictions, delays, or holding)

2. No priority for the SST as in the current ATC system

Concept I - SST handling with priority.- Concept I was the investiga- of experimental procedures for handling SST's on a priority basis. Basic changes in handling were in radar and altitude changes and the priority of sequencing over other aircraft. Present standards, figure 6, are 1,000 feet vertical and 3 miles radar separation in the terminal area and 5 miles radar separation enroute to flight level 29,000. Above 29,000, 2,000 feet vertical separation is used because of altimeter error.

22. New criteria under experimentation (fig. 7) were 1,000 feet vertical and 5 to 10 miles radar separation to 23,000. From flight level 24,000 to 54,000, 2,000 feet and 5 miles radar or 3,000 feet and 10 miles radar separation. At flight level 55,000 and above, 5,000 feet vertical or 10 nautical miles radar separation was tested.

23. Initial studies (refs. 1 to 4) indicated that a 1 to 4 minute vortex condition would exist behind landing and departing SST's. For the ATC tests, a standard 1 minute separation standard for arrivals and departures was employed. The 1 minute separation also applied to a cross runway operation until such time as additional study indicates a more reasonable standard.

24. It was also assumed under the priority Concept I, that the SST's were parked in a position for easy access to the runway and that after engine start could taxi unrestricted to a runway for an immediate takeoff, and after landing proceed to a parking area without delay.

25. During the simulation of Concept I, the following ground handling of the SST's was used:

1. Flight plans were filed 1 hour prior to Estimated Time of Departure (ETD)

2. SST's requested clearance 15 minutes prior to ETD

3. ATC clearances were delivered no later than 5 minutes prior to the proposed takeoff time

4. There was no ground delay in taxiing and no departures were released or arrivals sequenced 1 minute prior to the SST's arrivals. Departures were restricted when an SST was 8 nautical miles out on final

Arrival priorities and handling under Concept I:

1. No enroute or outer fix holding

2. Assured landings and programed departures

3. No altitude restrictions in climb or descent

4. Minimum radar vectoring, unless to the advantage of the SST

5. No ground delays

<u>Concept II - SST handling using current ATC handling procedures:</u> Normal ramp parking was assumed and taxiing to the active runway was accomplished by using the same taxiway as other aircraft. Radar and altitude separation standards were generally as outlined in the Manual of Air Traffic Control Procedures, AT P 7110.1A with the following exceptions:

A. The 1 minute standard separation for SST's for vortex dissipation was used

B. SST had to await their turn for takeoff and abide by local departure restrictions but were not held longer than 10 minutes when at the runway and ready for departure

C. Arrival delays for SST's did not exceed 30 minutes

26. A 200-nautical-mile area was found to be adequate for the oceanic runs with SST arrivals entering the problem at a cruise altitude of 60,000 or 70,000 feet and at Mach 3. Flights from the East and Northeast were cleared to the Deer Park VOR (DFK), as depicted on the area map, figure 8, and to Colts Neck VOR (COL) primary feeder fix for jet arrivals from the South, West, and Northwest.

27. It was assumed that adequate radar and communications existed throughout the area, that vortac facilities provided good navigational capability at all altitudes, that dual or parallel ILS approaches were authorized permitting simultaneous landings, and that an all weather landing system existed, the latter capability particularly for the later program phases.

PROCEDURES

28. Arrivals.- Generally, arrival SST's contacted the appropriate enroute sector, were identified and started on descent for approach and landing. After deceleration through the transonic regime at 50,000 feet and descent to below 40,000 feet, handoff to approach control was effected and the aircraft, now at subsonic operating speeds, was radar vectored to the instrument landing system for approach and landing.

29. Departures.- Generally, departures operating under Concept I or Concept II were radar vectored to a radial of a departure route navigational aid and climbed to cruising altitude as soon as possible or as dictated by a programed profile.

30. ATC test measurements:

1. Arrival and departure operations per hour
2. Communications
    a. Number of contacts
    b. Duration
3. Arrival holding delays
4. Total delays for SST's
    a. Departures - ground
    b. Arrivals - holding
5. Total SST Time in the system
    a. From departure to cruise
    b. From cruise altitude to touchdown

6. Number of SST

    a. Altitude changes

    b. Heading changes

    c. Frequency changes

31. Controllers.- Controllers, with at least 8 years of ATC experience in the field, manned the control sectors and positions of operation. A sufficient number of exploratory runs with different pilots and rotating teams of controllers were used to familiarize pilots and controllers with the procedures in use.

RESULTS

32. SST navigation.- Examples of problems experienced in navigation of the SST along present-day transatlantic arrival and departure routes are illustrated by figure 9. The solid lines and symbols represent the airway structure, the circles indicating VORTAC stations and the triangles overwater fixes. In addition to the usual airways, an alternate departure route formed by the 125° JFK VOR radial and the 260° Nantucket VOR radial was used. The dashed lines show examples of arrivals and departures in which the larger deviations from intended track occurred. Mach number (M) and flight level (F.L.) values are given at various points along the tracks.

33. In general, it can be seen that the deviations from track are of the order of 2 or 3 miles except where turns must be made at supersonic speeds. For the arrival from S. Bangar, the overshoot of course at Nantucket and resultant crossing of departure routes is a graphic illustration of a turn at supersonic speed not initiated until over the intersection. As can be seen, such an overshoot consisting of about a 2 minute excursion beyond the intersection, blocks the departure routes into Nantucket for departing SST traffic thus creating the need for increased buffers or separation. In order to avoid overshooting, the pilots were asked to make lead-type turns in which the turn is initiated at a given lead (DME) distance before the station. The lead distance information, based on the method of reference 5, was given the pilots in the form shown in figure 10. Examples of supersonic turns made in departures both using and not using the lead-turn method are illustrated in figure 11.

34. In addition to the problem of overshooting on turns at supersonic speeds, it was found that for departures such turns especially at low supersonic Mach numbers were quite detrimental on SST performance, since the SST excess thrust capability is at a minimum at low supersonic speeds. The departure turns required in

leaving the radials from JFK VOR (fig. 9) seriously affected the climb-accelerate capability of the aircraft. For transcontinental departures, the same problem is illustrated in figure 12. Again, large turns are required at low supersonic speeds. Such turns are not only undesirable because of the effect on performance, but in addition create intensified sonic boom levels because of the focusing effect of the turn. Estimates of the increase in sonic boom intensity resulting from focusing in turns range from 2 to 4 times. For departures, heading changes of any appreciable magnitude should be accomplished at subsonic speeds and a straight-line transonic acceleration track approximately 100 nautical miles long in which neither turns nor altitude restrictions are required, is desirable. As can be seen from studying the results shown in figures 9 and 12, however, with present-day routings in departures from JFK International Airport, the performance capability of the SST is such that only by operating the SST at subsonic speeds for up to twice the distance required to attain supersonic speed could straight-line heading along a 100-nautical-mile long transonic acceleration track be provided. Such extended subsonic operation for the supersonic transport would penalize SST operations seriously.

35. For arrivals, operations along the present airway structure were found to have little or no significant effects on SST performance. Turns at supersonic speeds such as required at Nantucket in arrivals from S. Bangar, figure 9, however, create intensified sonic booms and unless lead-type turns are employed result in overshooting of the intersection as discussed previously. Since, as can be seen in figure 9, descent into the altitudes used by current jet transport aircraft (30,000 to 40,000 feet maximum) does not occur until nearing Long Island, it appears that alternate routes could be developed for SST operations which would allow a direct approach to a point such as Hampton (HTO). Such a procedure would remove the necessity for significant changes in heading at supersonic speeds.

36. <u>SST flight path control</u>.- Examples of the ability of the pilots to manually maintain the scheduled climb and descent profiles are shown in figures 13 and 14. In the climbouts (fig. 13), difficulty has been experienced in maintaining the scheduled airspeed particularly in the altitude regime above 51,000 feet (570 KIAS). The difficulties in maintaining constant airspeed are believed associated with (1) the high performance capability of the SST, (2) an undamped phugoid characteristic, (3) need for variable pitch-trim rate, and (4) need for a more sensitive attitude indicator at supersonic speeds. Difficulty has also been experienced for the same reasons in following that part of the profile corresponding to the sonic boom overpressure level of 2.0 pounds per square foot (40,000 to 51,000 feet). In addition, during this portion of the profile, the pilot has no constant indications to follow since Mach number and altitude are increasing, and rate of climb is decreasing. Because of the difficulty of flight-path control, penetration of

the sonic boom boundary as shown in figure 13 occurred on many climbouts.

37. Less difficulty, in general, was experienced in maintaining the descent profile. However, in the example shown, figure 14, the pilot initiated descent from cruise prematurely and thus descended at too high an airspeed down to 50,000 feet. About the same difficulty with airspeed control occurs during this portion of the descent, as occurs during the high altitude phase of the climbout.

38. Studies are underway to explore the benefits of using the Flight Director as a means of guidance for flight path control during the climbouts and descents. The Flight Director has been programed to display an error signal representing the deviation in airspeed from the selected airspeed for constant airspeed operations, and has been programed to display the pitch trim input required to return to the scheduled flight path during the sonic-boom overpressure limitation phase of the climbout.

39. SST crew workload.- The workload for the SST crew created by operating in the air traffic control system for both ascents and descents are shown in figures 15 and 16. For the ascents, figure 15, assuming that the same number of frequency changes and message exchanges are required in handling subsonic jet transports as the SST, it can be seen that the workload for the SST crew is increased over that for the subsonic jets over the altitude range up to 40,000 feet. For the descents, figure 16, again assuming the same number of frequency changes and message exchanges, the workload for the SST is increased in the altitude range above about 10,000 feet.

40. ATC results.- During climb, lead time to level an SST at an altitude appears to be in the order of 5,000 feet below 40,000 feet and 10,000 feet above 50,000 feet. For the altitude range from 40,000 to 50,000 feet no appreciable lead time is needed and leveling would not be recommended because of low SST performance capability. During descent, lead time to level appears to be in the order of 5,000 feet above 50,000 feet and 3,000 feet below 40,000 feet until becoming subsonic.

41. In operations in which the SST was given priority (Concept I), subsonic traffic incurred long radar vectors, excessive holding, and ground delays. The delays for subsonic traffic were 13 percent higher in the priority concept than in the current system (Concept II). Airport acceptance rates were substantially reduced, in some cases by 14 operations per hour in the priority concept. There was no appreciable difference in the number of communications contacts although duration of contacts were longer under both concepts. Present voice communication procedures appear to be adequate for SST operations. SST time in the system increased by about 7 percent in the current system over that in the priority concept. Some of this time is attributed to fluctuations in adherence to profiles

and the increased separation standards both vertical and radar. Average total delay to SST's in the current system was 3.7 minutes per run. Insufficient data were obtained to assess ground queuing and departure delays under the current system. Controller subjective opinion was that separation standards for radar and altitude were too high and could be reduced. Limited preferential treatment can be provided SST's without adverse effects on the current ATC system. More expeditious ATC handling for SST's and subsonic traffic is possible through segregated approach and departure routes for SST's. Previous simulation studies, references 6 through 8, indicate that the combined use of an off-course computer and pictorial navigation (PD) display would provide a significant operational advantage to SST's. Unrestricted departure and arrival routes could be developed as depicted in figure 8.

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TABLE I

BASIC CAPABILITIES OF ATC SIMULATOR

Characteristics:	
Operating area (nautical miles)	400 x 400
Dual problem capability	Yes
Radar, search	Four
Radar, precision approach	One
Beacon (Mark X and ATCRBS)	All targets
Targets, quantity	60
Turn rate (degrees per second)	0-20
Speed (knots)	0-2500
Climb descend (ft per min)	0-8000
Altitude (feet)	0-100,000
Communications (Bell 300 switching system)	All positions
Flight simulator tie-in	Two
Digital data collection system	All positions

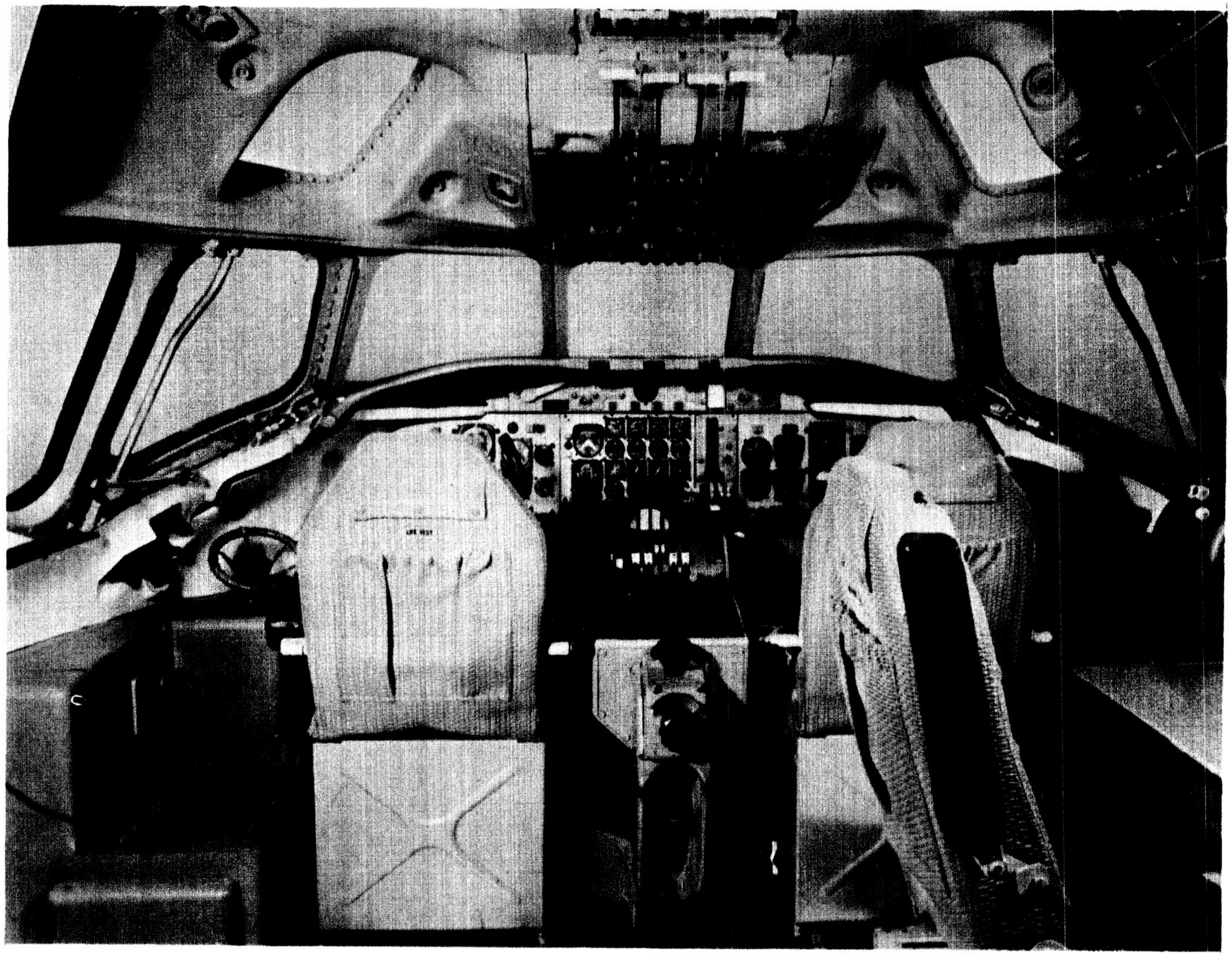

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Figure 1.- Interior view of the Langley fixed-base SST simulator cockpit.

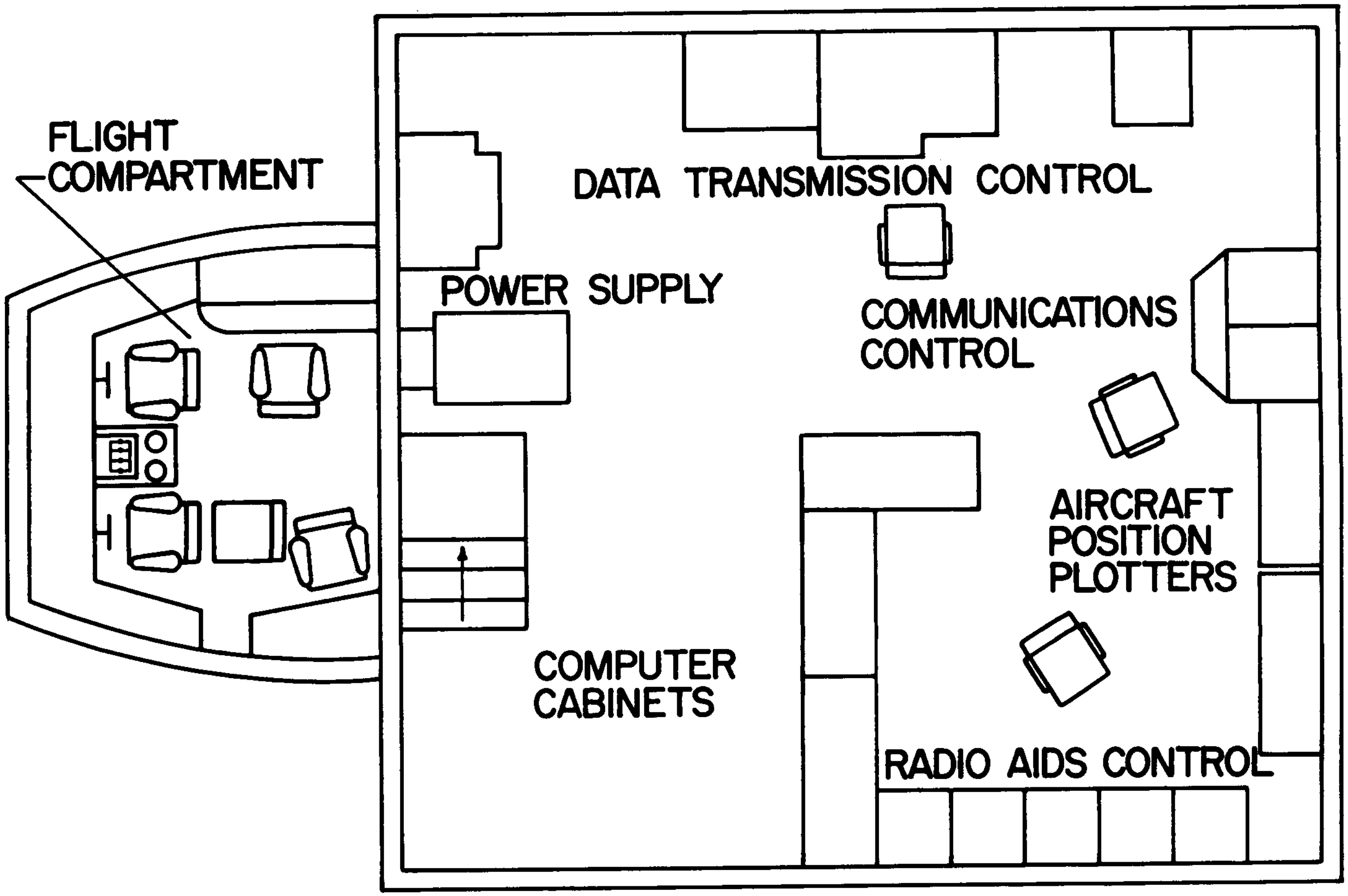

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Figure 2.- Langley SST simulator and control room.

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Figure 3.- View of simulated air traffic control center at NAFEC.

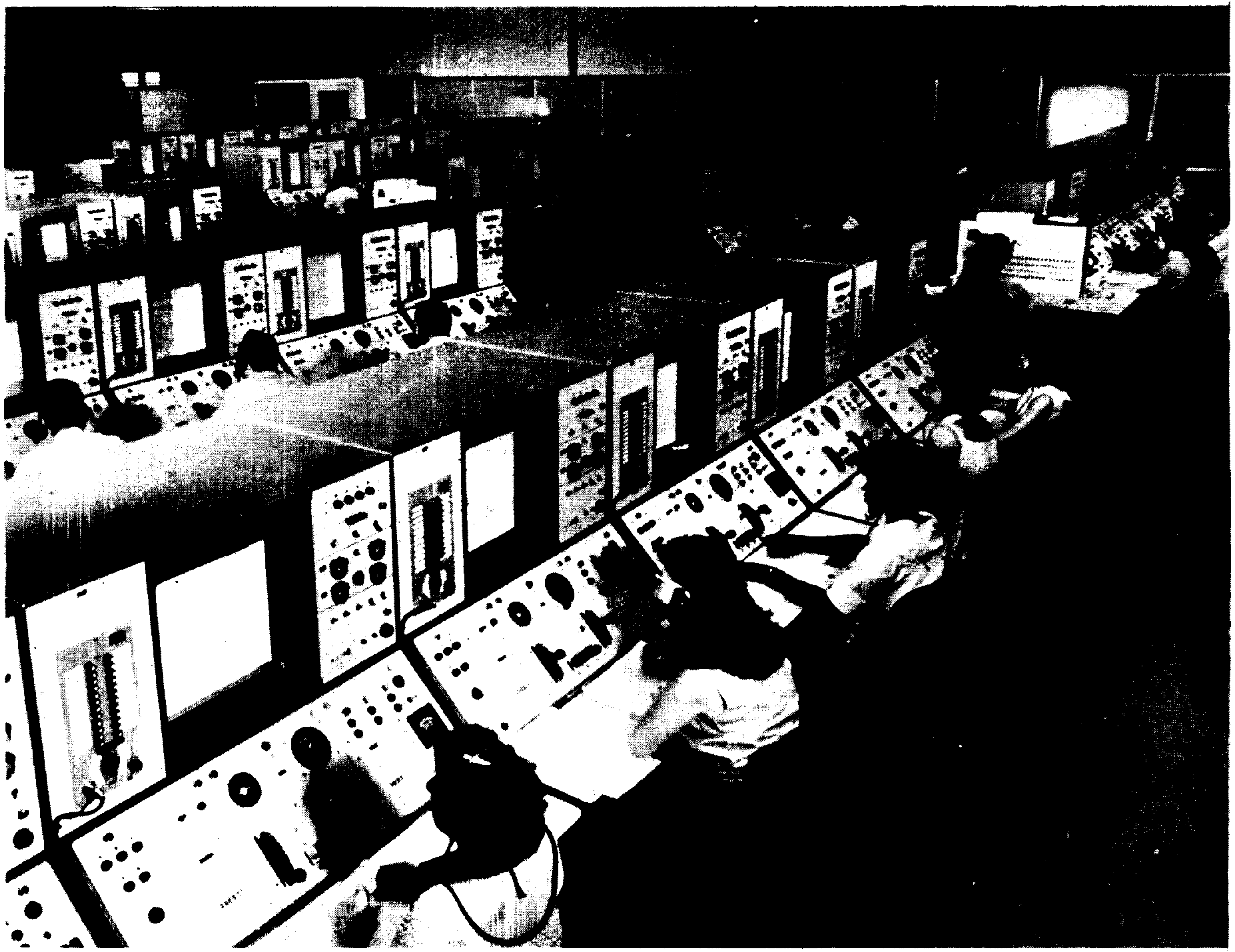

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Figure 4.- View of target generators at NAFEC.

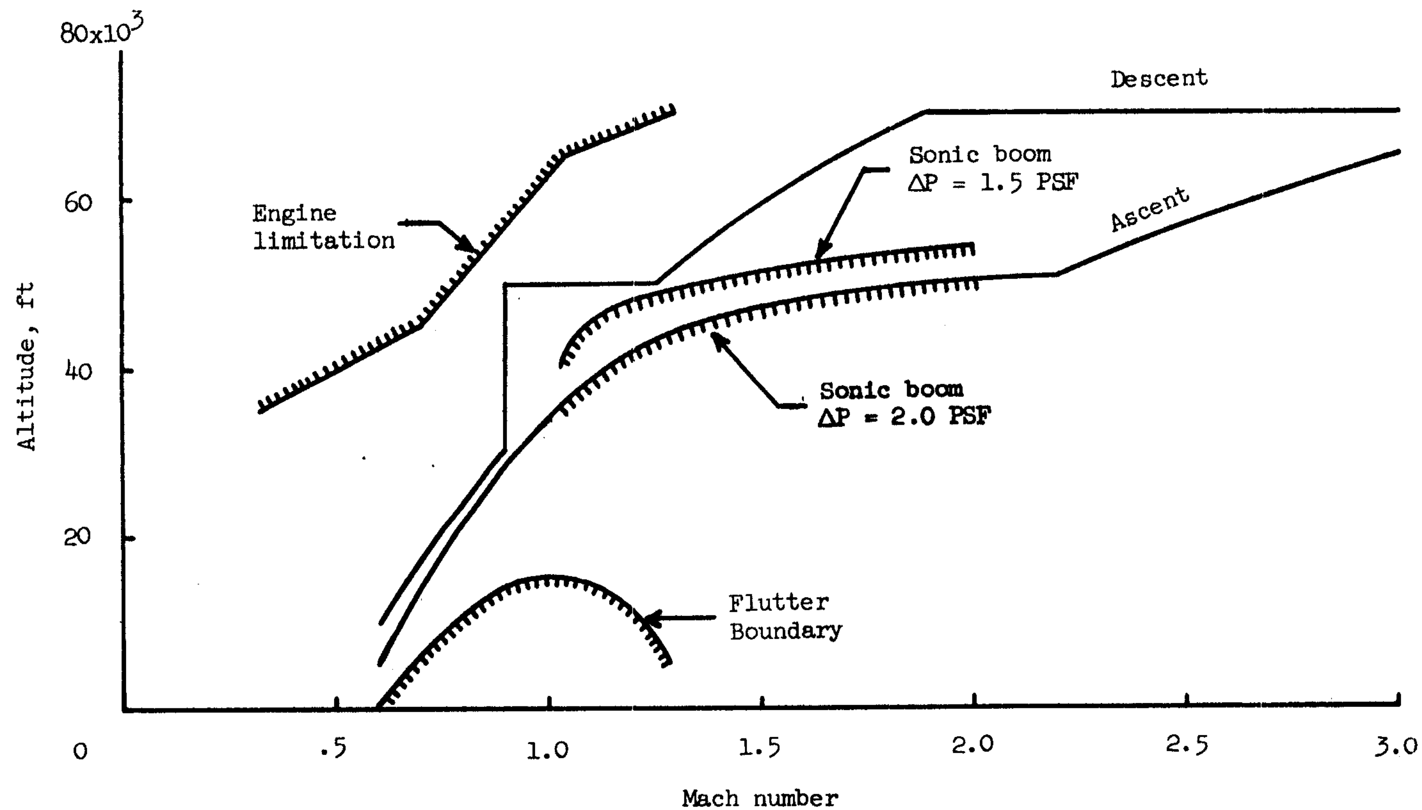

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Figure 5.- Arrival and departure profiles and operating boundaries.

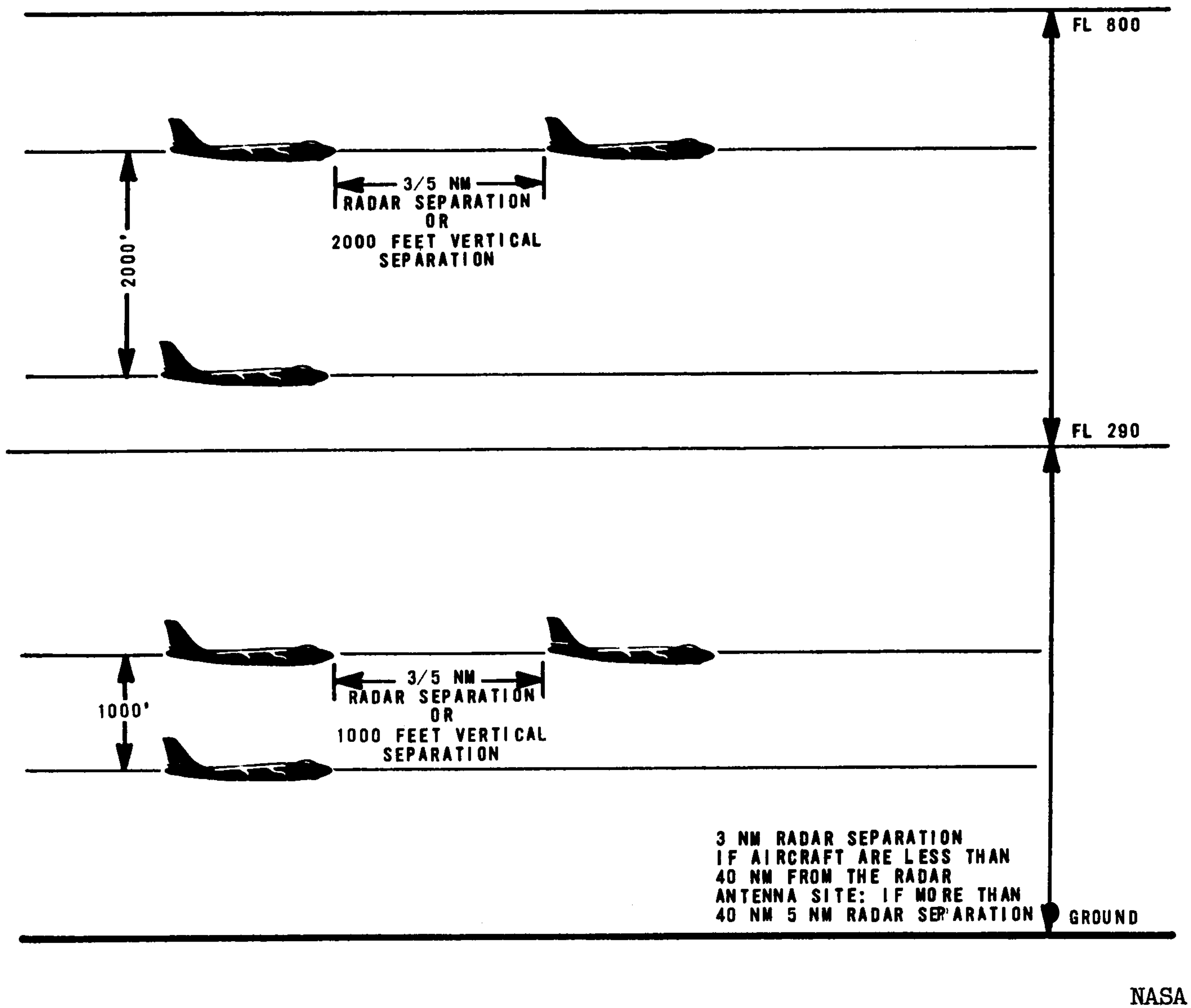

Figure 6.- Present-day separation standards.

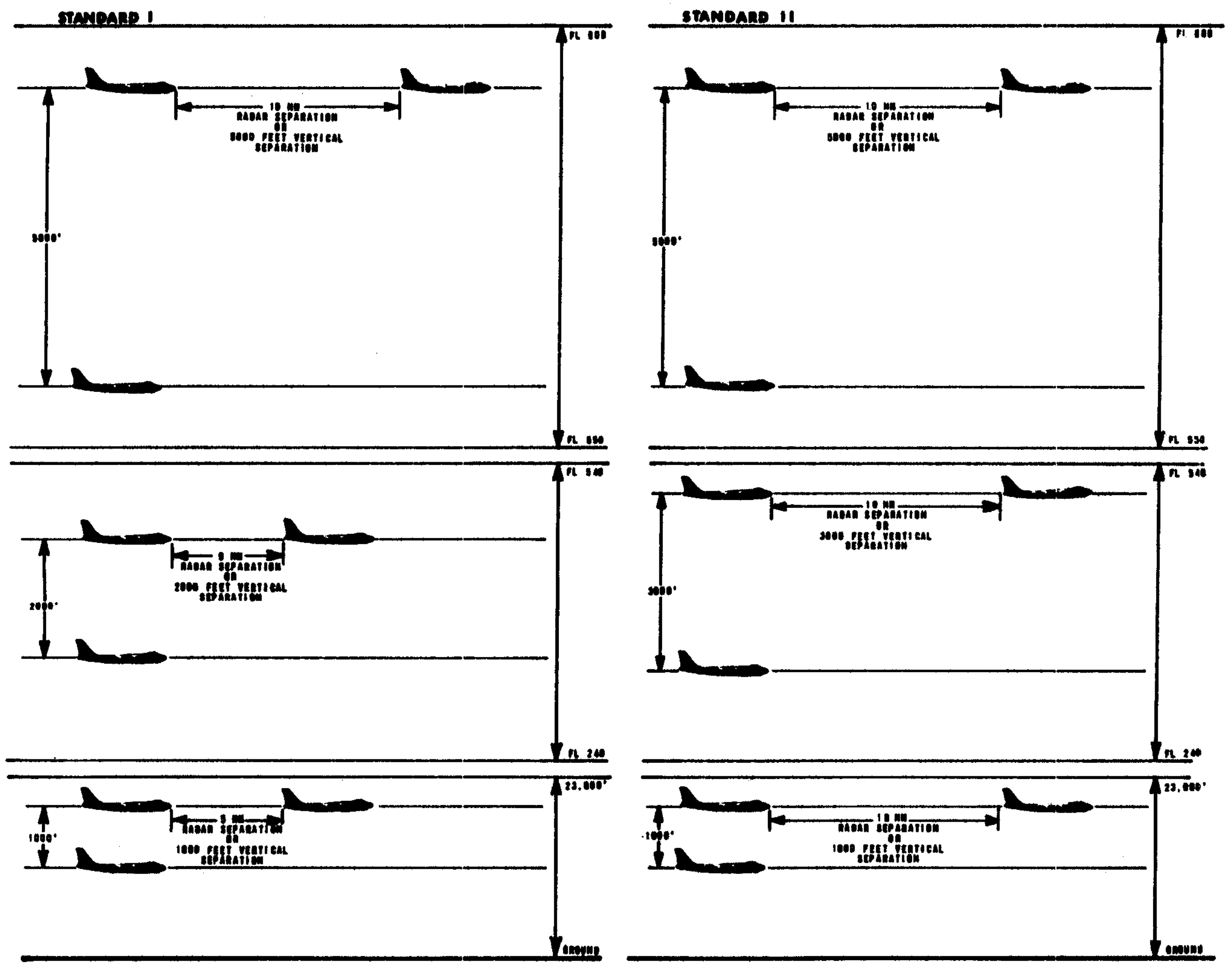

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Figure 7.- Experimental separation standards.

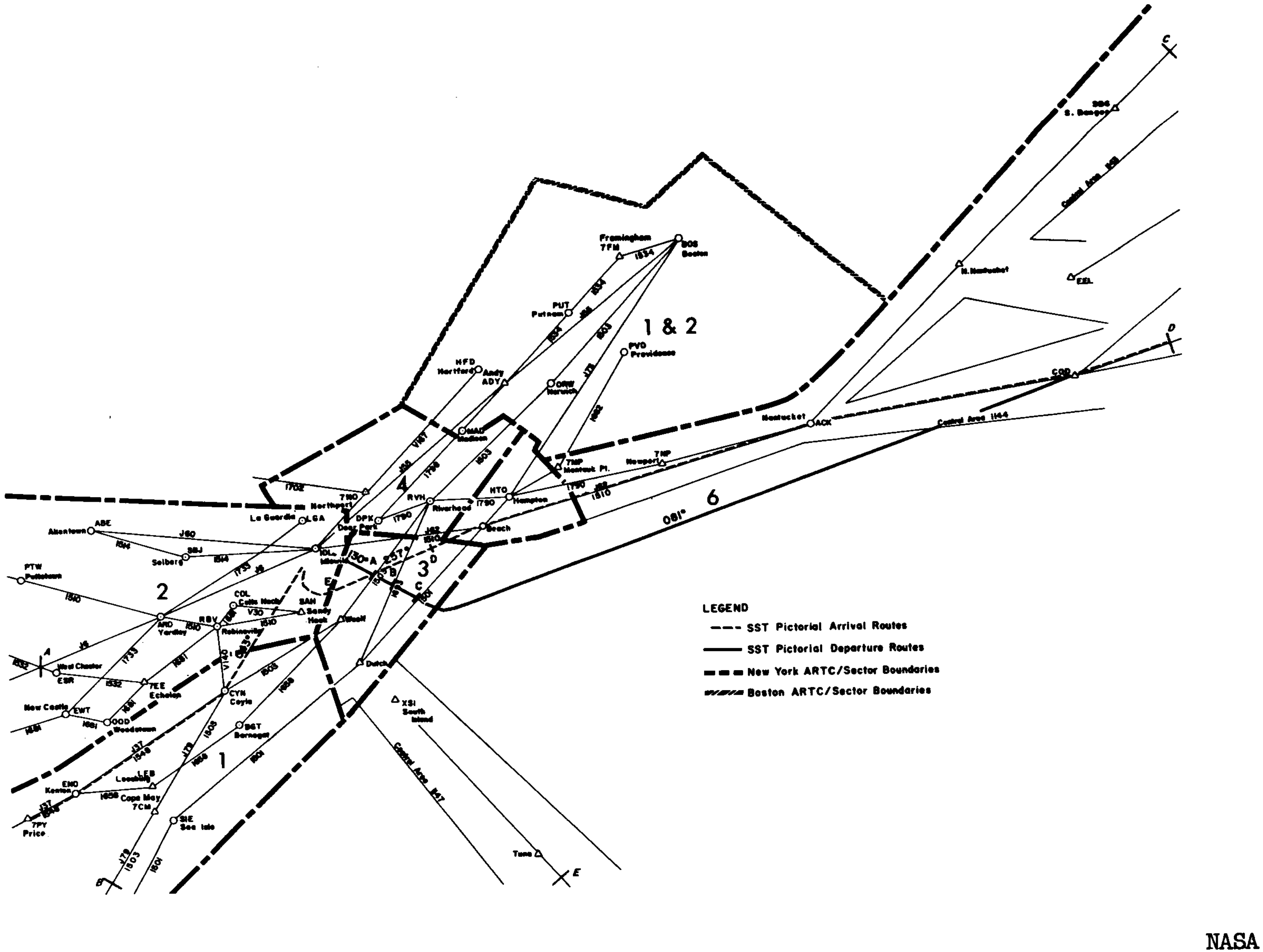

Figure 8.- Air traffic control area map.

Mach Number	Flight Time, min.	
	Departure	Arrival
1	8	10
2	18	6
3	23	0

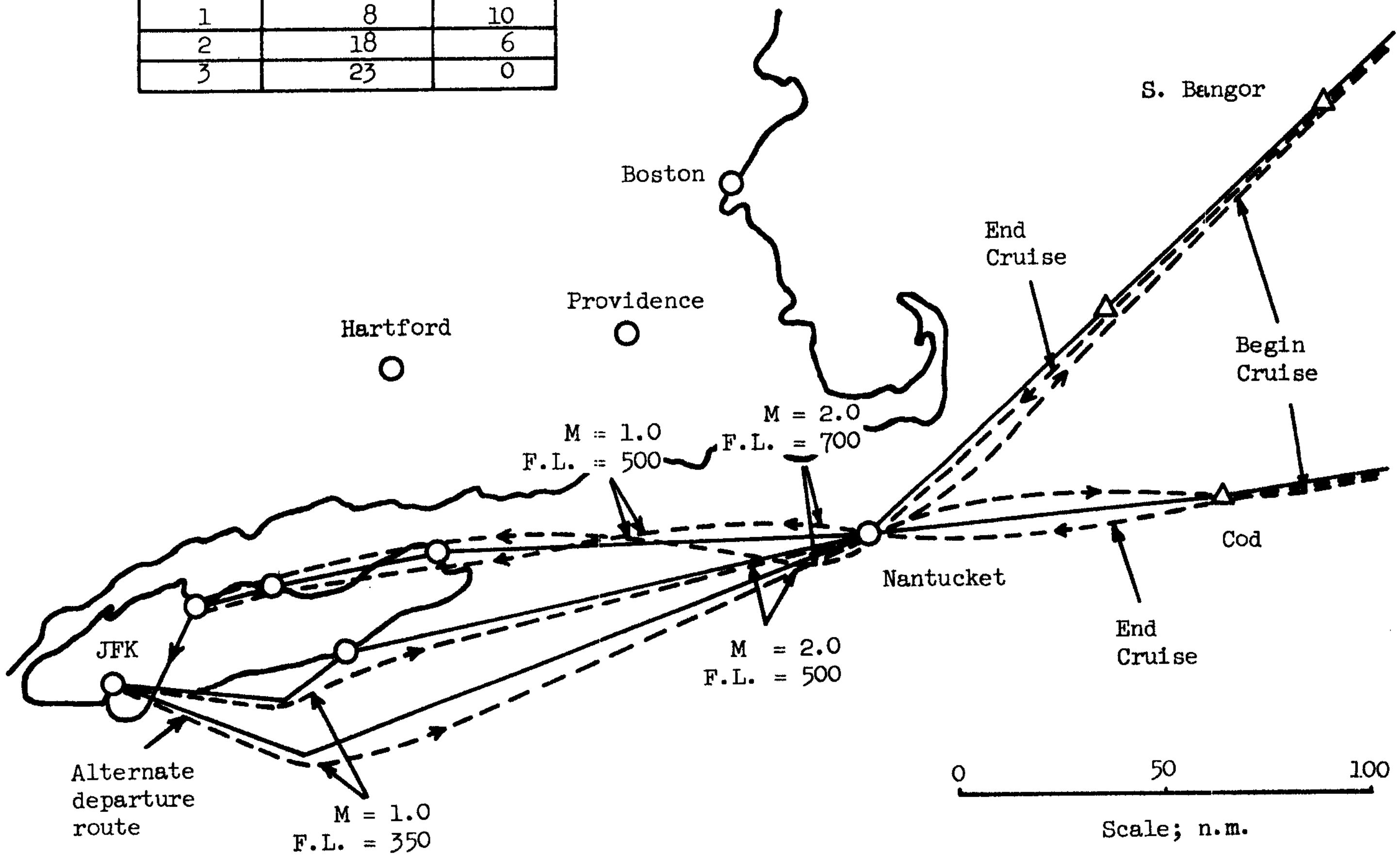

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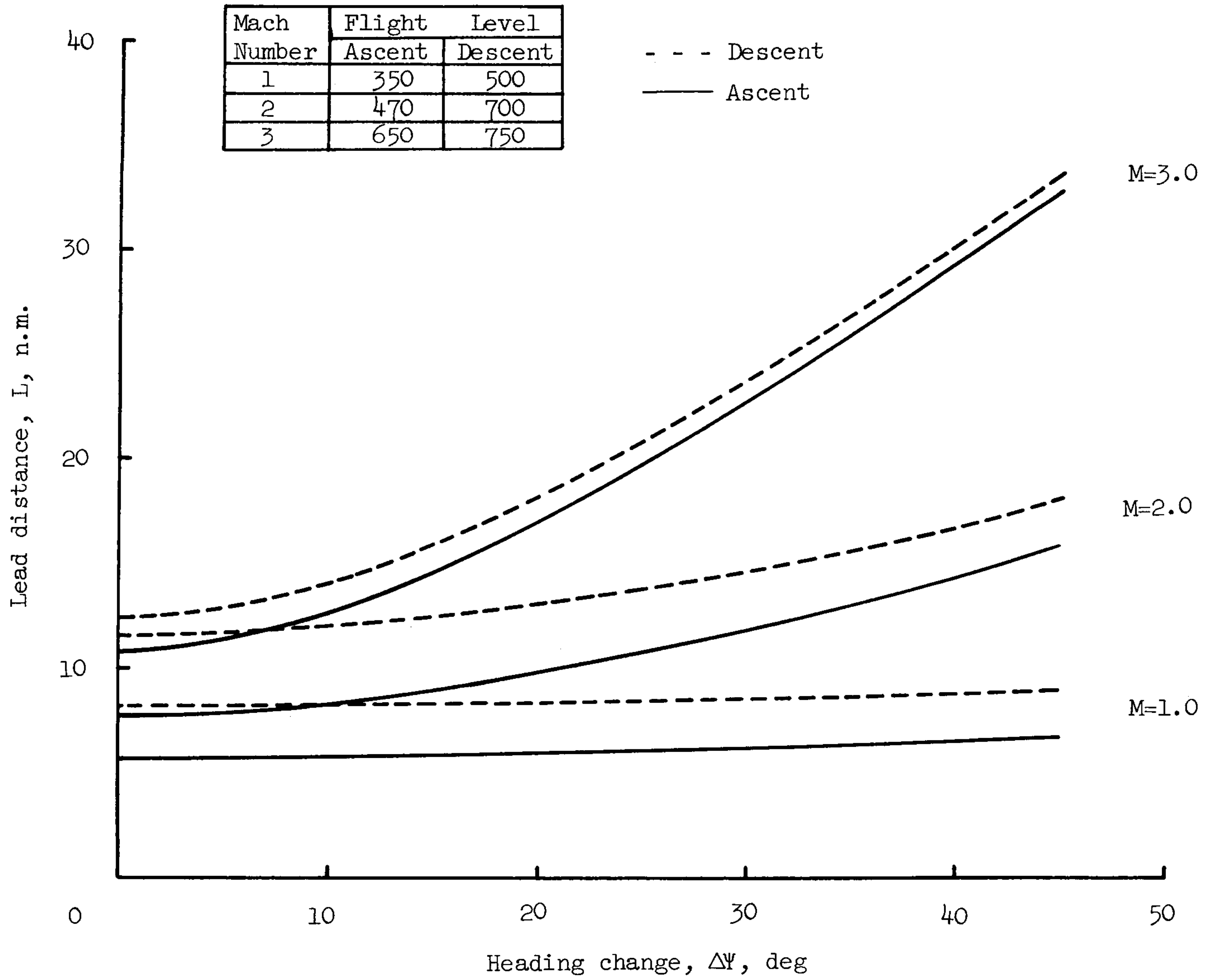
Figure 9.- Transatlantic departure and arrival routes.



Mach Number	Flight Level	
	Ascent	Descent
1	350	500
2	470	700
3	650	750

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Figure 10.- Pilot's lead distance information for making lead-type turns at supersonic speeds during scheduled ascents and descents.

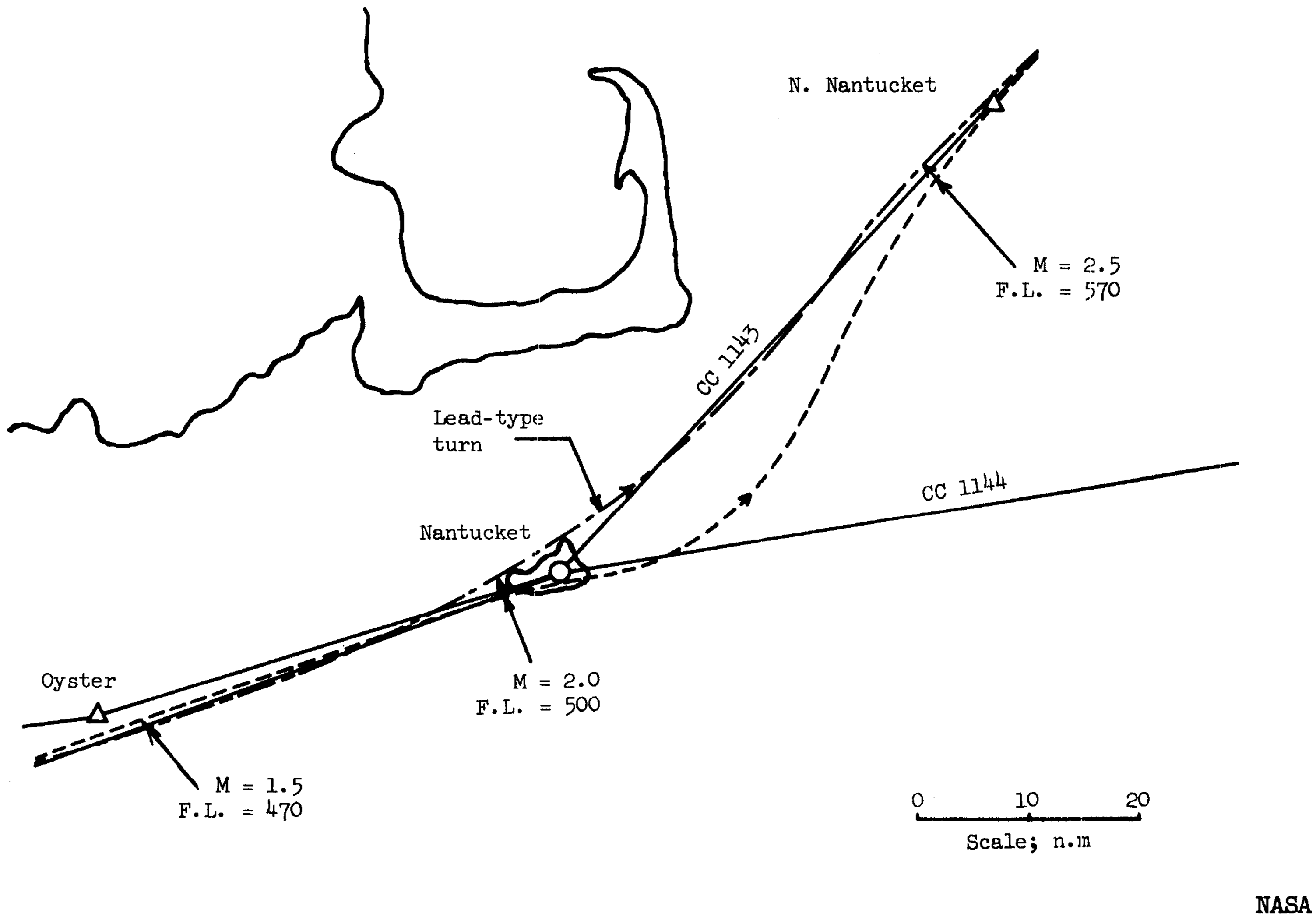

Figure 11.- Examples of lead- and nonlead-type turns.

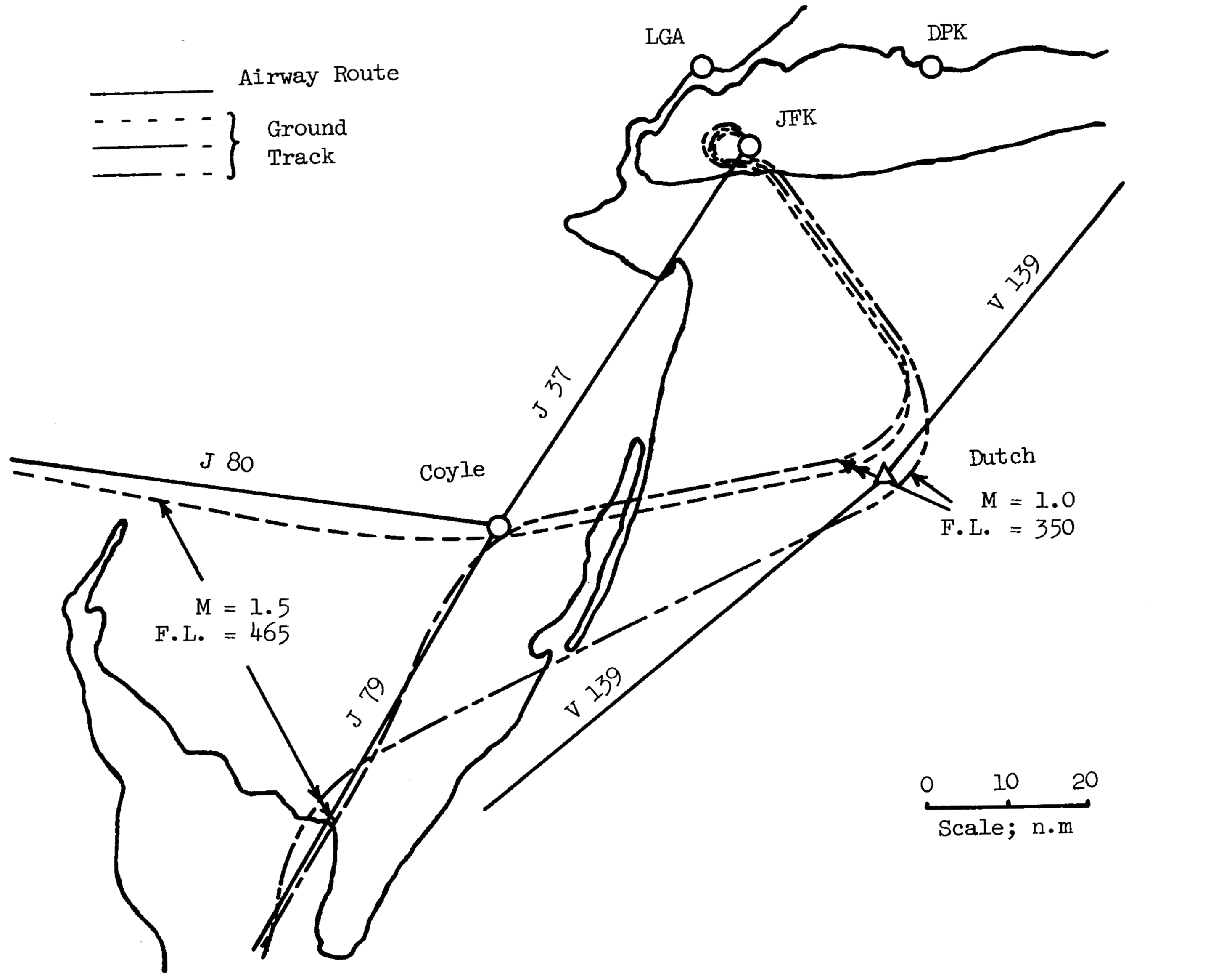

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Figure 12.- Transcontinental departure routes.

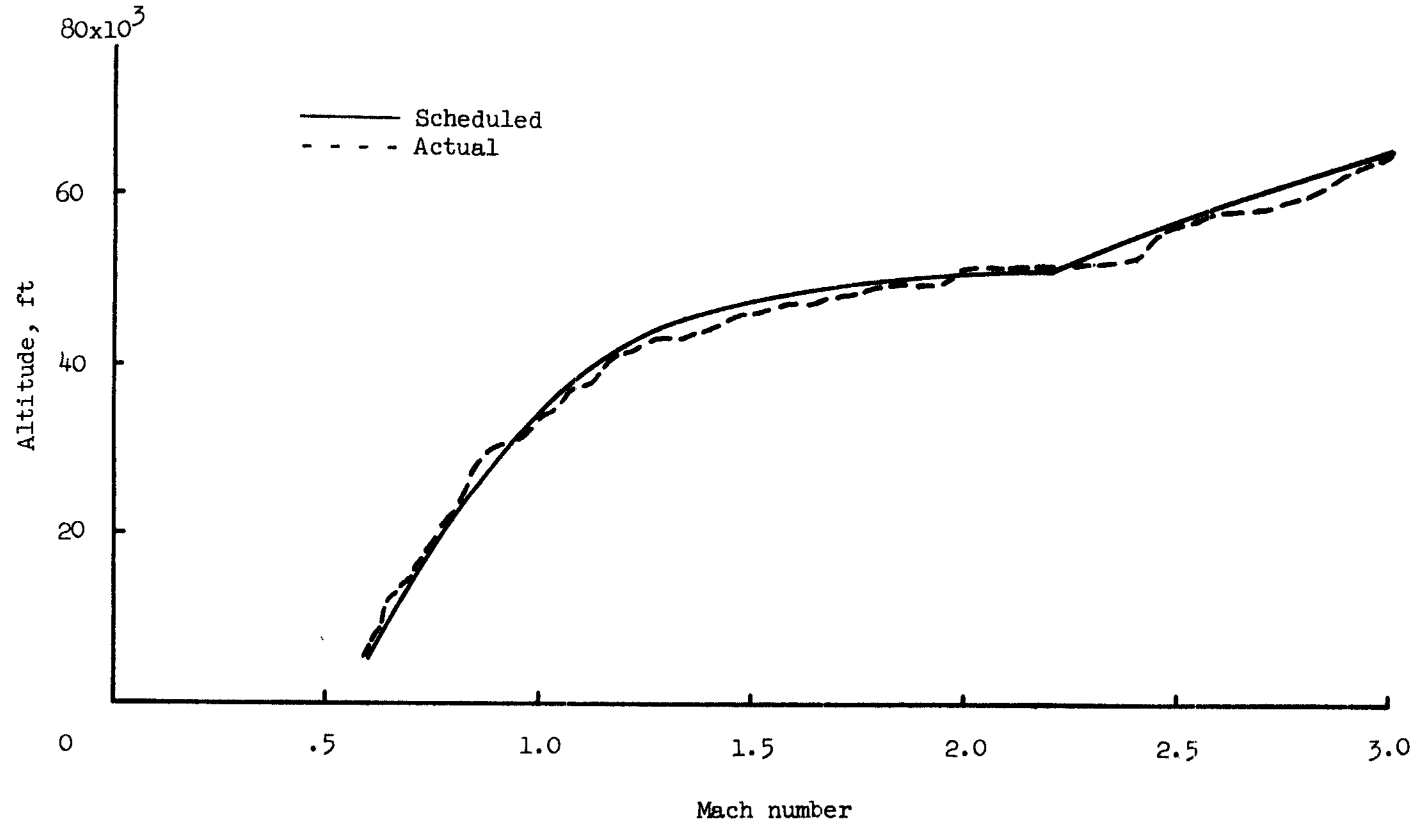

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Figure 13.- Scheduled and actual ascent profiles.

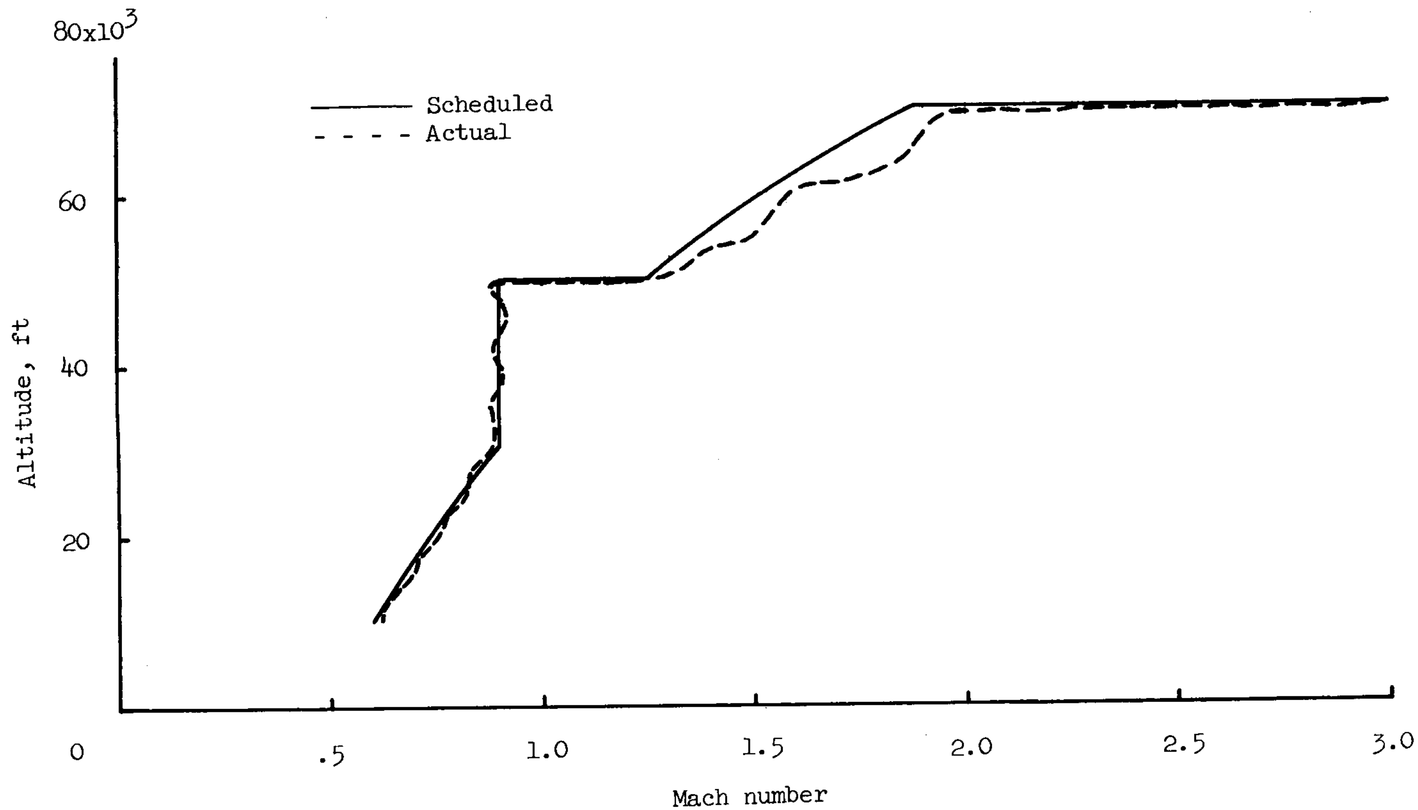

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Figure 14.- Scheduled and actual descent profiles.

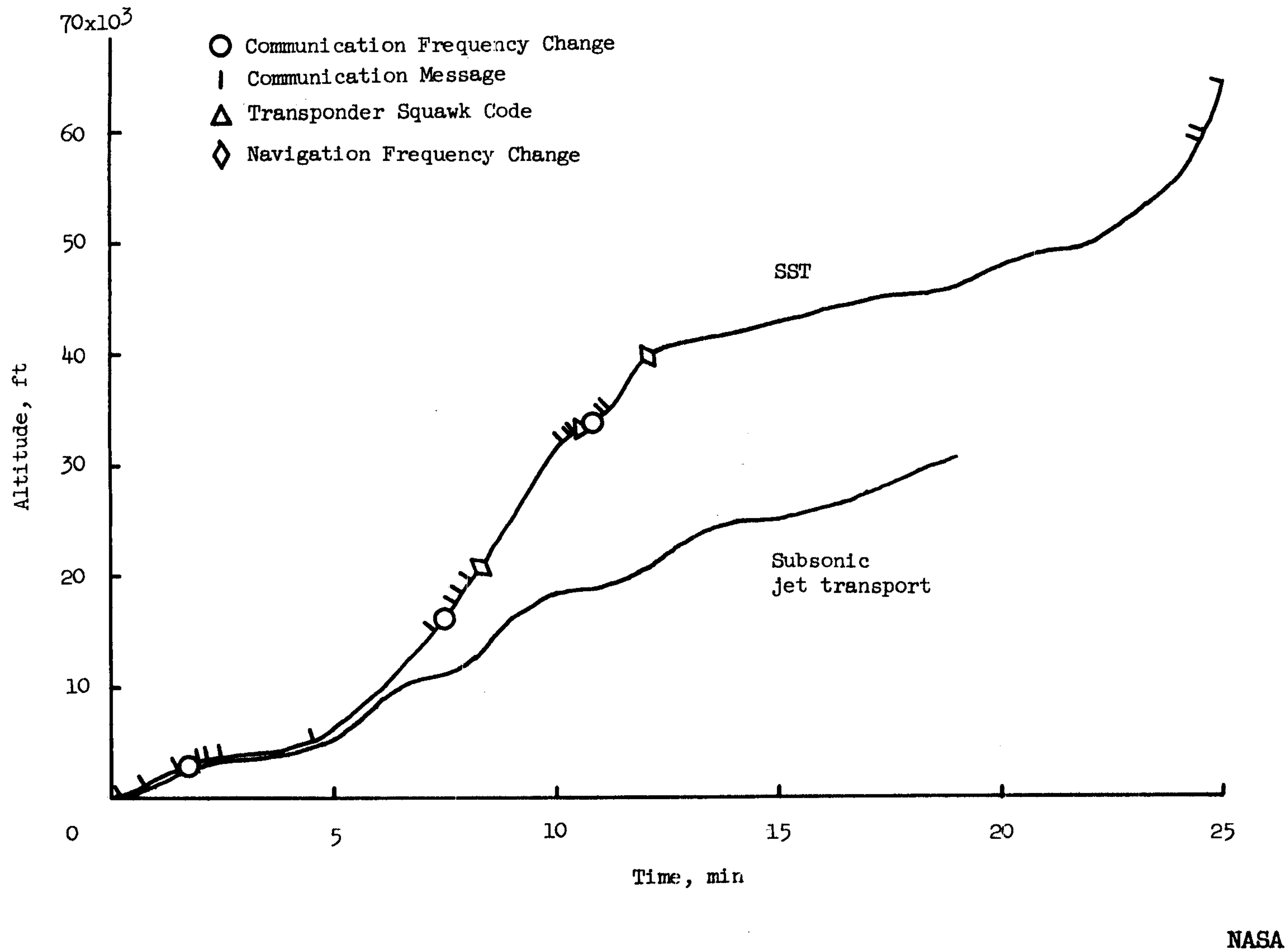

Figure 15.- Crew workload during ascent.

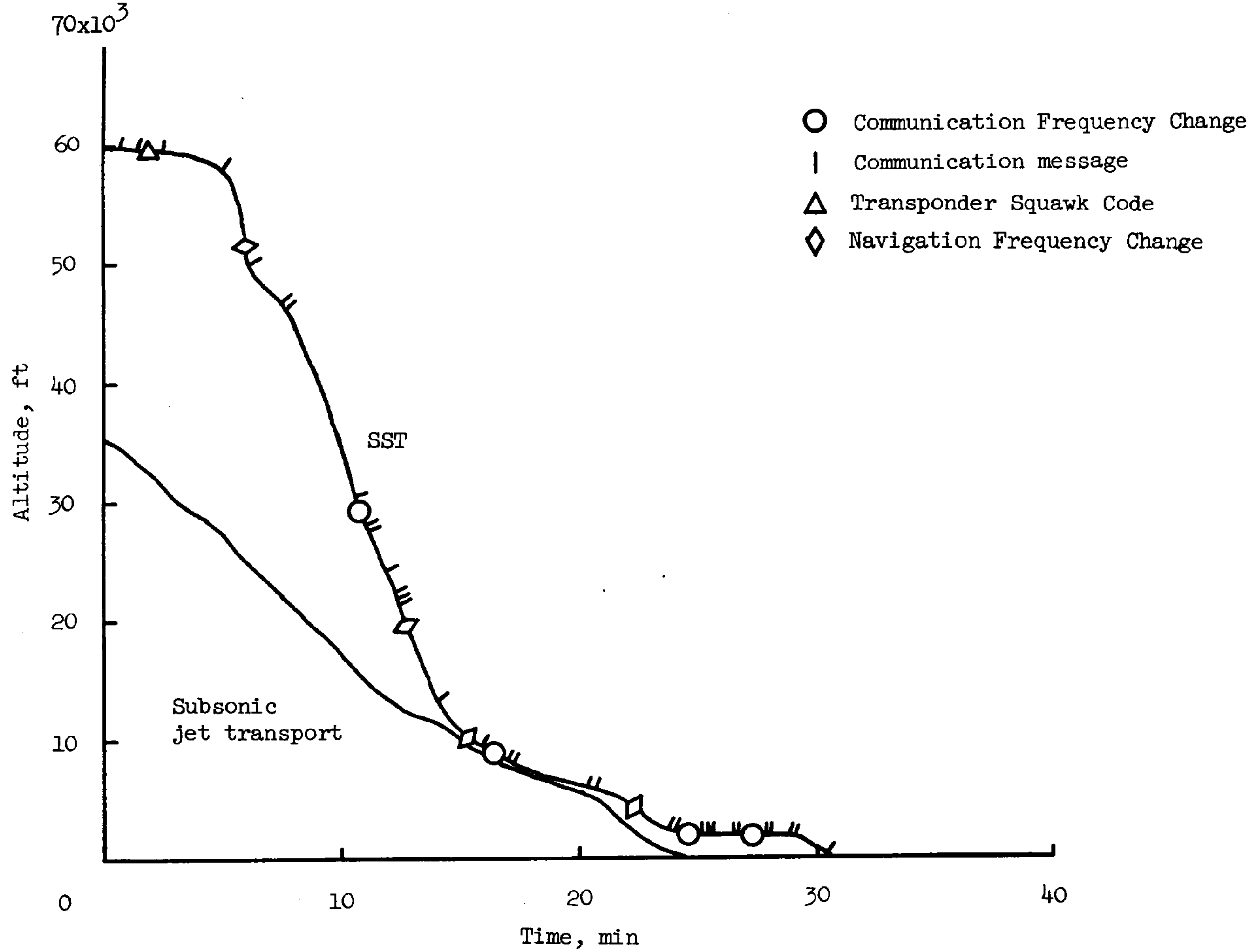

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Figure 16.- Crew workload during descent.

NASA-Langley, 1965